THE ROLE OF TIME AND FREQUENCY IN FUTURE SYSTEMS

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INTRODUCTION

Over the last twenty years, the Global Positioning System (GPS) has revolutionized the performance and the geographical availability of time and frequency dissemination, while at the same time reducing the cost to the individual user. This paper examines the question of what comes next for time and frequency dissemination. The question has two motivations: How can improved performance be achieved in the future, and how can redundant sources of time and frequency be provided to critical systems? A model is developed for time and frequency dissemination based on the time management performed in GPS. Several candidate systems for future time and frequency distribution are identified. One system–SONET telecommunications–is discussed in detail. Performance requirements and hardware implementations are presented.

SYSTEM MODEL

The implementation of time and frequency distribution begins with a model for the operation and management at the system level. In order to successfully integrate time and frequency into future systems, the time has to serve both internal system requirements as well external customer requirements. There are lessons to be learned from the GPS system on the requirements for the management of time. The GPS system provides a good model for the successful integration of internal and external requirements. Thus, the initial model for embedding time and frequency into future systems is based on the features and characteristics of how time is implemented in GPS.

GPS is an operational system serving military and civilian requirements. The system contains 24 satellite clocks as well as monitor station clocks, to form a distributed clock set which provides clock intercomparisons by virtue of the very operations of GPS itself. From the clock intercomparisons, GPS computes a composite time (a timescale that becomes the GPS time). The feature of time transfer within the system is built-in and automatic. It has a robust system architecture which is maintained, centrally managed, and globally available for recovery of

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Universal Coordinated Time (UTC). GPS time itself is steered within what only a short time ago would have been considered to be very narrow limits. In addition to the steering of GPS time, GPS broadcasts UTC corrections, providing the user the capability to determine if and/or how the local time will be steered to UTC. No matter what steering algorithm is used, there is always a differential between the physically realized time at the user and the system time (UTC or GPS in this case). That differential is known and reported to the user, but not necessarily removed instantly.

The fundamental system requirement that is gleaned from the GPS model is that time and frequency within the system are provided as a by-product of the system operations. Unlike WWV, which was designed to disseminate time, the GPS system was designed to support a navigation mission with a timing sub-mission. GPS has set the standard for excellence in the field and time-transfer performance. Future systems that will be of interest for time dissemination are going to perform at comparable or better levels. They will probably have comparably very large costs. It will take billions of dollars to implement systems that can provide worldwide globally available timing to the tens-of-nanoseconds level as GPS does. So it is unlikely a stand-alone timing mission would be implemented with the phenomenal cost that would be involved. On the other hand, the cost of timing that is provided within major systems like GPS is only a few percent of the total system cost.

Just as the timing mission is not a stand-alone mission, the timing expertise must not be isolated, either. If the timing community is going to advance, the timing expertise must be distributed to the system level. It is important that on the operational level, people running these programs and systems truly have their own expertise, and not rely on experts located at centers of excellence.

FUTURE SYSTEMS

One candidate for future systems which will require time and frequency distribution is a Department of Defense (DoD) project known as Global Grid. It's a concept for aggressive worldwide distribution of information, communications, and information processing. The Global Grid concept will use established government and commercial assets for communications, i.e. government and commercial satellites, optical fibers, and telecommunication systems utilizing established protocols such as SONET and ATM. Currently, there are many aspects of Global Grid that are being worked and demonstrated by multiple organizations. Three examples are the Global Broadcast System (GBS), Personal Communications Systems (PCS), and laser-based satellite communications (LASERCOM). These examples are discussed separately below.

The Global Broadcast System utilizes geosynchronous satellites for the one-way broadcast and dissemination of information. Adding the precise satellite position to the information downflow enables GBS to deliver precise timing to a user with a known position. Presumably, a stationary user with a known position can achieve 10 ns precision for time recovery. In fact this kind of precision has been demonstrated on an experimental basis by some of the commercial satellite companies. Such a system could also augment GPS by providing pseudolite signals.

In the Global Grid architecture, the Personal Communication Systems (PCS) represent the last mile of the communications systems. Often a commercial link exists (via satellite or cable) to an end point which does not serve the user, who may be deployed in an undeveloped or unstable area. The PCS systems are used to get information out to the individual in the field. Such systems often utilize wireless links. These links can be satellite-based or a combination of radio links and land lines. Time and frequency signals could be delivered to the user via

these PCS links for many military applications.

Laser communications (LASERCOM) will be used for satellite downlinks in future systems. Laser downlinks are occasionally interfered with by weather (Fig. 1), prohibiting the signal being received at a ground station. The impact of local weather on the ability of a ground station to receive the optical signal creates a requirement for multiple options for ground stations and the ability to seamlessly switch between ground stations. The transition from one ground station to another results in massive changes in signal path delay. The downlink is eventually fed to a synchronous optical communications system and it will be necessary to cope with the synchronization of data at the hub. The challenge of such a system is going to be the management of the path delays. Time recovery and synchrony at each ground station will be required to fuse the data at the high bit rates that are possible with LASERCOM systems.

SONET IMPLEMENTATION

One possible implementation that will be applicable to future systems is the use of the Synchronous Optical Network (SONET) to disseminate time and frequency as a by-product of the transfer of payload data. SONET (or SDH) is being used to implement precision timing and precision frequency management both within the U.S. government and elsewhere. Nippon Telephone and Telegraph (NTT) has been publishing[1] and working with the ITU for many years in this area. In this paper we use a SONET system as an example of how precise timing (an order of magnitude better than GPS) may be implemented within a communications system. One of the advantages of using a communications system is that, for the most part, the traffic is two-way. This enables the implementation of two-way time transfer, which is the traditional technique for delivering high precision time. The current operating level of GPS with regard to delivering time is only quasi-two-way. One way is the management of the system through the monitor stations and master control station, and the other way is the delivery of the information to the user, but the two directions are asymmetric. Large offsets in time and large offsets in geolocation between the two links limit the performance of GPS time delivery to somewhere in the 10-25 ns range.

The implementation of precision timing within communications is being driven today by very high precision timing users with different agendas. However, the synchronization of networks in the time sense would be a significant benefit to all communications timing users. Time synchronization of network nodes can eliminate path changes as a source of wander on SONET or SDH networks. This results in allocating the entire wander budget to sources other than the path changes that currently dominate the calculation. This wander budget determines the ability to reconstruct analog signals, such as voice and facsimile, when the signals travel over the SONET network for long distances. Such a synchronization system will serve all time users (all the way down to the private branches) who in any way connect to the network at the OC-3 level or higher.

An architecture and a time code have been developed for SONET-based time and frequency dissemination. Hardware has been developed for this application and is currently under test. The implementation plan starts with point-to-point and extends to LAN, over the air, platform distribution, MAN, transoceanic cables, and WAN. The system conforms with the standard aspects of the NTT proposal and serves the long-term goal to be consistent with the standards that may be adopted by the ITU sometime in the future.

The SONET architecture is seen in Fig. 2. There are four network nodes with a multiplicity of network elements separating the nodes. One node is connected to a master timing unit that

provides the interface for an Ultra-High-Precision (UHP) clock system or a primary reference clock. Slave units connect to other nodes and re-derive signal sets which are steered to the master via two-way time transfer. The system also supports future goals of using the two-way SONET link to measure clocks which are connected to the slave nodes. This allows the clocks to be located at the remote slave nodes and still measured (via SONET two-way) at the nanosecond level for inclusion into the time scale. This concept of a distributed time scale (the clocks are distributed geographically) provides for clock ensembling without the requirement of maintaining the clocks in one central location. This increases the reliability and the robustness of the system without a performance trade-off.

The current goal for time and frequency distribution using SONET is to distribute a standard time and frequency set consisting of one standard frequency, high quality 1 PPS, and time code. The goal is to transfer performance that is representative of a cesium standard with a high-performance tube with time transfer accuracy of two nanoseconds. Two nanoseconds represents an improvement of approximately a factor of ten over what users are now able to do globally using GPS. The SONET system must be automatic, with no external calibration and support redundancy in automatic switch-over. Point-to-point time synchronization supported by such a system is limited by the SONET standards, which can communicate over ten kilometer fiber-optic cable. The system must also support higher quality future clocks and transfer that performance to the user.

This SONET system is an implementation and demonstration program (as opposed to a research program) which requires the use of standard, commercially available, telecommunications quality, zero dispersion single-mode fiber using standard connectors. Due to the path delay changes that are incurred on a fiber in a nominal environment, two-way time calibration is a requirement to support a 2 nanosecond accuracy specification. For example, a 10 km fiber with a 70 degree centigrade maximum environmental swing from dead of winter to heat of summer exhibits an approximately 60 nanosecond change in path delay. Extending this to a 3000 km SONET link in a network results in a 5 microsecond change. The basic approach is to use the synchronous SONET transport as a vehicle for the time code needed to perform two-way time transfer. The SONET payload is inappropriate for this application due to the ambiguity involved asynchronous data transfer. The transport for SONET at the physical layer supports synchronous data transfer, which is an appropriate vehicle for two-way time transfer.

The two-way time transfer is supported by a master/slave relationship between network nodes. The master encodes a time marker in the SONET overhead, which is measured at the time of transmission and measured once again at the slave at the time of reception. Similarly, the slave transmits a time marker that is received at the master. The two measurements performed at the master are transmitted to the slave in the time code, where they are used to compute the master-slave time difference, independent of the delay between the two locations. At the slave end, a clean-up loop recovers high quality frequency signals. It has been demonstrated that a clean-up loop with a bandwidth of 1 Hz can meet the specifications of a high-performance cesium standard. The clean-up loop uses one-way measurements. Therefore, its output is subject to temperature-variable delays, which are corrected based on the two-way measurements. This delay compensation is done by averaging the phase measurements in order to reduce the measurement jitter below the local clock time error. The slave local oscillator is held on frequency by calibration compared to the master clock.

CONCLUSION

This paper uses GPS as a model for designing time and frequency systems which are embedded as by-products of primary mission objectives. This is done to defray the substantial cost of achieving high quality time synchronization. It is proposed that communications and data dissemination will be the next vehicle to provide system redundancy for GPS in the timing area and improvements in GPS timing performance. A SONET architecture is presented which conforms to the proposed model, and performance specifications are presented.

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[1] M. Kihara, and A. Imaoka 1995, *"SDH-based time and frequency transfer system,"* Proceedings of the 9th European Time and Frequency Forum (EFTF), March 1995, Besançon, France.

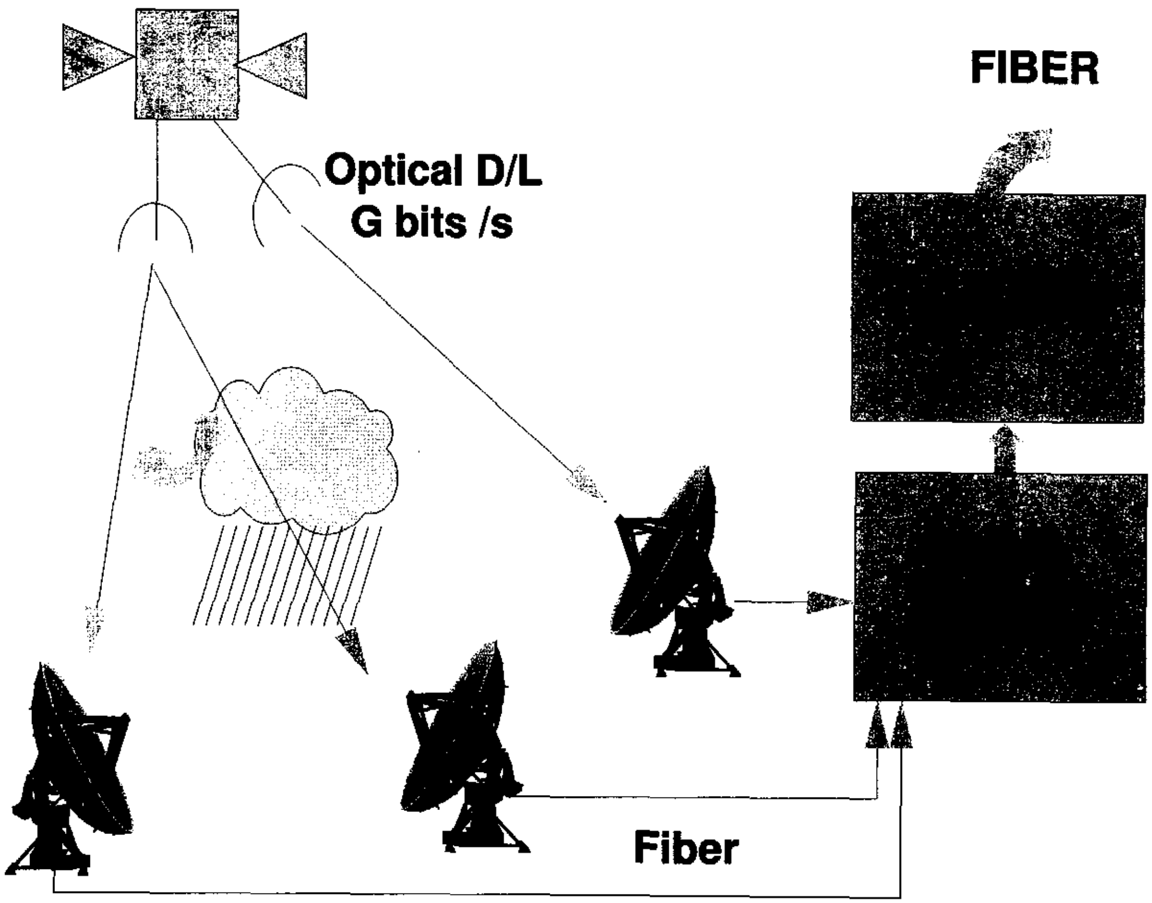

Figure 1. Switching LASERCOM downlinks changes the path delay.

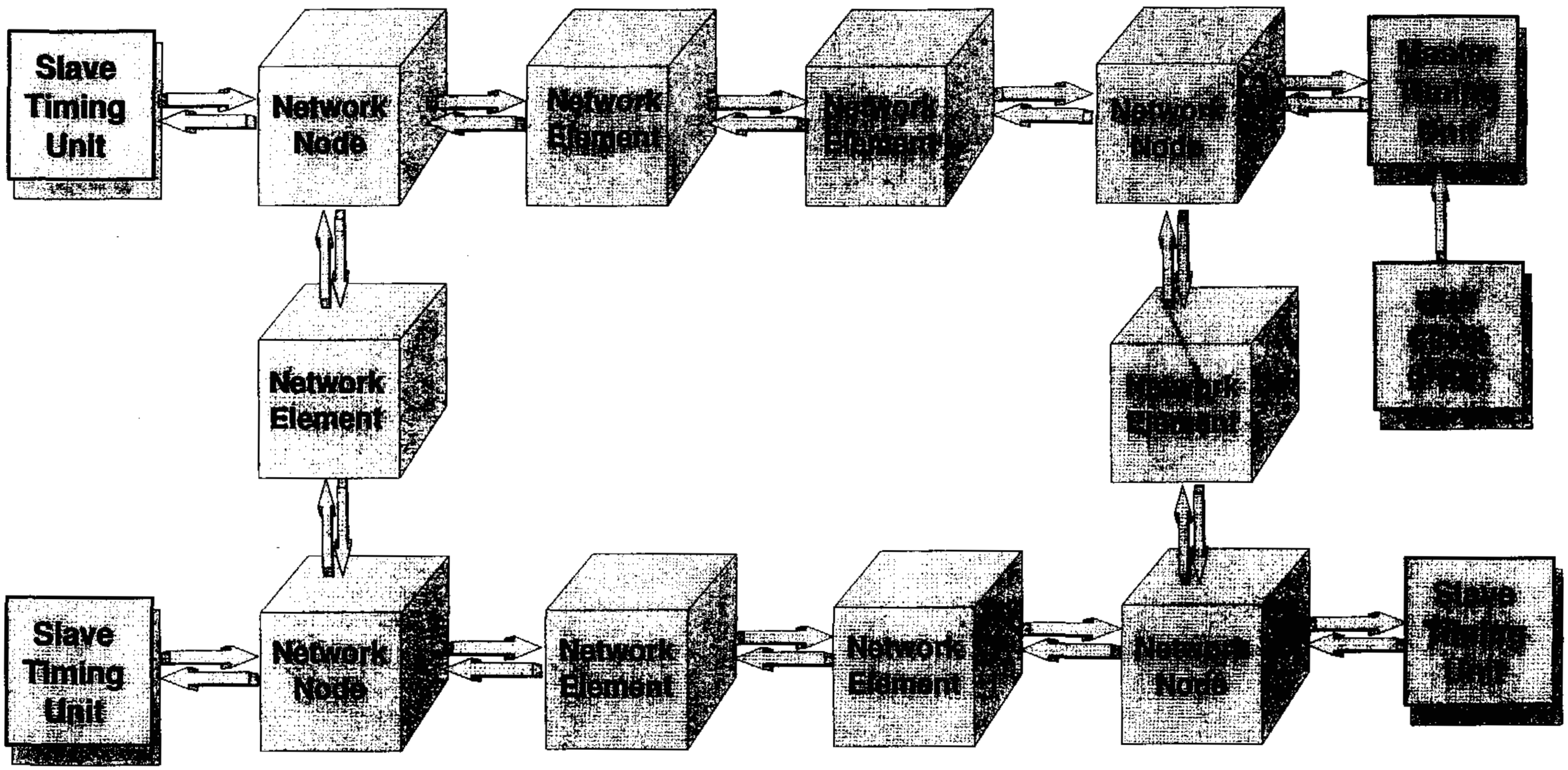

Figure 2. SONET loop with a master timing unit and three slaves.